"VOLTAGE STABILITY ANALYSIS USING PHASOR MEASUREMENT UNIT"

DISSERTATION-II

Submitted in partial fulfillment of
the award of the
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With specialization in
Power System

By

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I, **DOLLY CHOUHAN** student of M.Tech (Electrical Engineering) under school of electronics and electrical engineering of Lovely Professional University, Punjab, hereby declare that all the information furnished in this Dissertation report is an authentic record of my own work carried out under the supervision of **Ms. VARSHA JAISWAL,** Assistant Professor /Associate Professor School of Electronics and Electrical Engineering. The matter presented in this dissertation has not been submitted to Lovely Professional University or to any other university or institute for award of any degree.

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The M.Tech Viva–Voce Examination of __________________ has been held on ________ and found satisfactory/Not satisfactory.

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CERTIFICATE

This is to certify that DOLLY CHOUHAN bearing Registration No. 11503031, has completed objective formulation of thesis title **"VOLTAGE STABILITY ANALYSIS USING PHASOR MEASUREMENT UNIT"** under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of the thesis has ever been submitted for any other degree at any University.

The thesis is fit for submission and the partial fulfilment of the conditions for the award of **MASTER OF TECHNOLOGY (ELECTRICAL ENGINEERING).**

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I, Dolly Chouhan student of M. Tech. (Electrical Engineering) under Department of Electrical of Lovely Professional University, Punjab, hereby declare that all the information furnished in this thesis report is based on my own intensive research and is genuine.

This thesis does not, to the best of my knowledge, contain part of my work which has been submitted for the award of my degree either of this university or any other university without proper citation.

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ABSTRACT

In power system, due to the various disturbances and contingencies, states variables gets deviate from their limits and causes instabilities in the system. Hence there is a need for analysing these variables. Continuous changes in these variables i.e.; voltages are gathered together and used by the State estimator. The disadvantage of the traditional state estimator is that they are immature to consider these dynamics of real time and are more sensitive to the measurement error. Henceforth to avoid this problem, Phasor Measurement Unit (PMU) is collaborated with the traditional State Estimation (SE) method. Phasor Measurement Unit (PMU) is a promising tool because it provides the phasor measurement of voltage and current of the bus. Apart from its application in SE, utilities are being using it for protection and control schemes.

This dissertation provides a brief knowledge of the voltage stability as its measure is used in the state estimation. Changes in the values of voltage occurs due to the changes in the load. Its evaluation has been done by varying load and for different load cases, varied voltage value is noted. To perform SE, Weighted Least Square (WLS) method is used. Since these methods provides the nonlinear estimate, direct measurement of the PMU is used to form a matrix which can directly estimate the result without going to the whole iterative method. Voltage stability has been deduced by the use of the several Voltage Stability Indices (VSI) ,P-V,Q-V and Eigen value. These VSI gives the closeness of the system toward the voltage collapse. Standard IEEE 14 bus test bus system has been chosen for analysis part using MATLAB R2015a software.

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ABBREVIATIONS

FASE	Forecasting-aided State Estimation
FVSI	Fast Voltage Stability Indices
IEEE	Institute of Electrical and Electronics Engineers
NR	Newton Raphson
OPP	Optimal Placement Problem
PMU	Phasor Measurement Unit
P	Active power
P.U.	Per unit
Q	Reactive power
SE	State Estimation
SSE	Static State Estimation
VSI	Voltage Stability Indices
VCPI	Voltage Collapse Proximity Index
WAMS	Wide Area Measurement System
WLS	Weighted Linear Least Square

CHAPTER 1
INTRODUCTION

1.1. BASIC OVERVIEW

Our power system is prone to many contingencies and disturbances . In recent years major blackouts have been recorded throughout the world . Disturbances such as loss of line or generators , surges , faults , changing of load and so on can cause the system's operating points to deviate from the limits . In order to account on these problems and to find out the reasons of their occurring, one has to see these important parameter related to all this phenomenon i.e. voltage.

Voltage instability will also incorporates the abnormal conditions like transient instability , oscillations and so on. It is the prime duty of the engineer to maintain the steady limits of the voltage to be in the range before and after the disturbances . Hence it is needed to find the corrective measure or control for static voltage stability and optimal solution to have a keen observations on the power system dynamics so that it could help to sort out the contingencies and helps in effective planning of the system with greater reliable operation of interdependent critical infrastructures.
Several researches has been done to find the corrective control for strategic static voltage stability. . Real time monitoring of the system is required for the fast control and online solutions and implementation to mitigate these challenging problems.
Synchronized phasor measurement technology is basically new in this field. It has found applications in control .protection and so on.. Even algorithms and simulations are so developed that they are now a part of real time power system and successfully running.

1.2 OVERVIEW OF THE WORK PRESENT IN THE REPORT

The main aim of this dissertation is to describe the voltage stability and how it gets deviated from its operating point under the disturbances. Moreover it focuses on the need of PMU incorporation with the traditional state estimation technique to make the system observable. Various voltage stability techniques has been given for analyzing the voltage stability. It includes P-V curve, modal analysis method and various indices such as FVSI, VSI, Lmn, VCPI indices. The remaining of this report comprehends eight chapters.

Chapter 2 emphasizes on the Synchronized phasor measurement units and along with their optimal placement and their wide applications in power system and describes the state estimation and need of incorporation of PMU into it.

Chapter 3 recalls an overview of voltage stability . It includes basic definitions associated with voltage stability and classification of instabilities and different analytical methods. This chapters describes the different indices used for estimating the voltage stability

Chapter 4 is devoted to detailed literature review on OPP of PMU and its application followed by voltage stability description in which types of the indices and causes are explained. In addition to it, introduction to state estimation is also described and its application need in in the power system using PMU has been discussed.

Chapter 5 describes the objective of the thesis

Chapter 6. gives the research methodology which is carried out on the IEEE 14 bus system. .In this proposed methodology, NR method is opted for load flow analysis and state estimation technique is done using weighted least square method. In addition to it, optimal placement of the PMU is done by greedy algorithm. Calculation of FVSI, LQP, Lmn, VCSI, V/V0 line stability indices has been deduced.

Chapter 7 discusses gives outcome and describes how it will be beneficial to improve the current scenario. It shows the scope of study giving us the need of the use of PMU for resolving voltage stability problems occurring in the system and how it will be beneficial for future generation methods.

Chapter 8 gives the summary and future scope of this thesis work.

CHAPTER 2
PHASOR MEASUREMENT UNIT

2.1 HISTORICAL DEVELOPMENT:-

In early 1980's, that very first paper which identifies the importance of positive sequence phasors and its measurement usage can be considered as the initial point for the modern synchronized PMU. The first prototype using GPS was built at Virginia Tech which was deployed at some stations of the Bonneville Power Administration, New York Power Authority, American Electric Power Service Cooperation. In 1991, first commercial manufacture of PMU was built by Macrodyne and Virginia Tech [10]. This led to an outcome of the 1965 catastrophic failure which was happened at North eastern power grid in North America [9]. For example, blackout happened in 2003 in North eastern U.S. and in 1996 U.S. West Coast , leads to have an urge for having PMU for analysis [13].

2.2 PHASOR MEASUREMENT UNIT (PMU):-

It is a monitoring device whose data are in the phasor form which are the complex representation of sine waves comprising magnitude and phase angle together in the electrical signal. These are also called as the synchrophasor as it allows both angle and magnitude at a same instant. For absolute time reference, synchrophasor uses coordinated universal time (UTC). One pulse per second signal is being generated by precise clocks and this is taken as a reference for PMU. They take data generally from scattered location in the network and these data are time stamped in a space of 1µs for synchronization with the help of a common time source. Hence the PMU measured voltage and current data are time stamped. Not only they measure phase voltage and current, they also measures the frequency and positive sequence parameters all in a cycle. Once they are synchronized they can be compared in the real time. Therefore their inclusion in the power system stations will be critical and are needed to make our present grid smarter [45].

But the main issue regarding its application is their site selection. The cost of pmu's limits their installation number. But it seems that its increase in future might decrease their cost. It is important to have an optimal placement of PMU [17].

2.3 BASIC PMU STRUCTURE [45]:-

It consists of

1. **Synchronization Unit**:- It involves GPS receiver and phase locked oscillators which provides sampling clock to measurement unit. Whole network needs fast data transfer within the sampling frequency of phasor data. On the other hand ,GPS time stamping provides accuracy of synchronization even better than 1 μs. Control system's output signal gets compared with the phase of input signal. Control's output signal is generated by electronic circuit which consists of variable frequency oscillator and a phase detector. Role of the phase detector and variable frequency oscillator is to compare the phases of generated signal and input signal and matches the phases of these signals respectively.

2. **Measurement Unit**:- It has three components namely, Antialiasing filters, A/D converter and processor.

S.no.	COMPONENTS	FUNCTION
1	**Anti aliasing filter**	• Made by using analog front end and a digital decimation filter which are stable from ageing and temperature point of view. • Verifies the same phase shifts and attenuation of all the analog signals which ensures that parameter of different signals have unchanged magnitudes and phase differences. • Signals are continuous in time and are analog in nature.
2	**Analog to Digital (A/D) converter**	• Signals from filter are then converted to digital signal whose nature is of discrete time and amplitude
3	**PMU/processor**	• Helps in achieving the large scale deployment of PMU integration into modern technology where relay uses the microprocessor.

Table 2.3.1 :- Measurement unit's components and their function

Receiving of the data from measurement unit is done by MODEM. MODEM stands for modulator-demodulator. It is used to transmit more than one analog signals at a time.

3. **Data Transmission Unit**:- Transmits the measurement data further. At sending end, analog carrier signal gets modulated and digital information is encoded before transmission whereas at the receiving end it gets demodulated to decode the data.

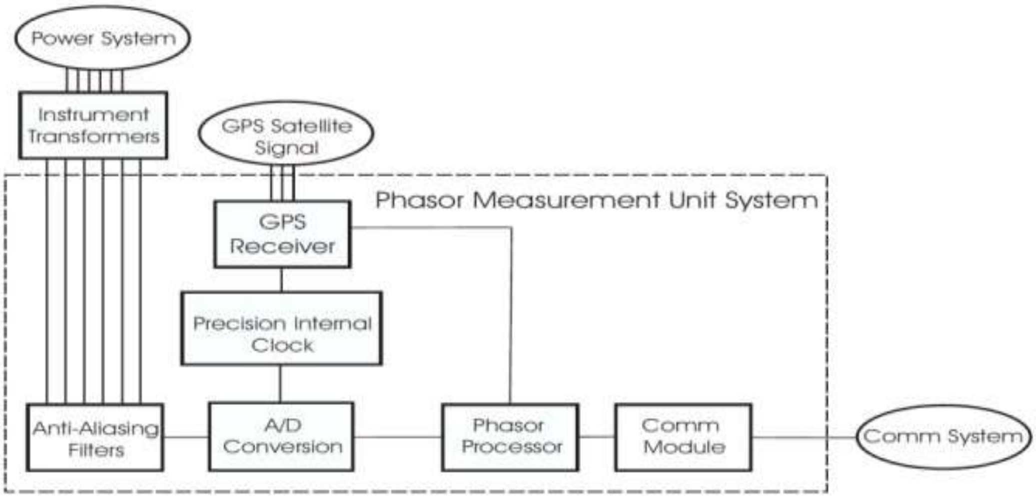

Fig 2.3.1 :- Basic PMU structure[45]

Fig 2.3.2: - Vendor PMU Offerings (Macrodyne)[48]

2.4 IEEE STANDARDS:-

Two IEEE standards are there namely, COMTRADE and SYNCHRNOPHASOR. COMTRADE standard is in a report of CIGRE study committee SC34. Based upon the

COMTRADE standard, SYNCHROPHASOR standard was made after seeing the wish of PMU users who wants to have PMU's interoperability among different manufacturer. This was formulated by Power System Relaying Committee which comes under IEEE Power Engineering Society [9].

2.5 OPTIMAL PLACEMENT OF PMU:-

Since it is not economical to place PMUs at each and every bus to diagnose/detect the problematic area, so we need a placement technique which will provide a complete observability of the system. Placement techniques will depend on the PMUs application, installation restriction and the system characteristics as it is not even necessary also to place at each and every bus. Many topological and numerical methods are there to define the optimal location of PMUs. But we aims to find out the one technique or the combination of techniques which will not only minimize the installation cost but will also provide full observability using a minimum set of phasor measurements. Earlier methods like linear (LP), non-linear (NLP), dynamic programming or combinational optimization are used. These techniques are all conventional optimization techniques. But they have certain disadvantages like handling of constraints are complex, tedious, or numerical difficulties. Therefore other optimization techniques i.e.; heuristic and modern meta-heuristic are there which includes minimum spanning tree (MST), depth first search (DeFS), tabu search (TS), differential evolution (DE), genetic algorithms (GA), ant colony optimization (ACO), or particle swarm optimization(PSO) [7][14][22][31][41][43][44].

2.5.1 PROPOSED METHOD:- GREEDY ALGORITHM [44]

Description: - For the placement of the PMU using the greedy algorithm, buses with the maximum connectivity is chosen for the PMU placement to ensure the system's observability. Hence problem of placing PMU on all the buses will be reduced to a greater extent. For the execution of the algorithm, connectivity matrix C_{PMU} of dimension N_{bus} X N_{bus} is made by converting the elements of admittance matrix in the form of binary number. Elements of the matrix will be defined as:-

$$C_{PMU} = \begin{cases} 1 & , if\ i = j \\ 0, & otherwise \end{cases}$$

Its objective is to minimize $\sum Xi$ where X_{i} = PMU buses such that,

$$C_{PMU.}\, X \geq [1]\, N_{bus}\, x1$$

where $X=[x_1, x2, \ldots\ldots\ldots. x_{Nbus}]$

If above said condition is met then system is said to be observable else unobservable. For maximum connectivity of the bus, sum of each column of C_{PMU} is done. Highest sum corresponding to the column ,that column will be bus location where the PMU will be placed.

Sum= $\sum$ $C_{PMU,}$ will be a (1x N_{bus}) matrix.

Placement of the PMU on any bus, updation of the visibility matrix occurs again same dimension whose elements belongs to [0, 1] on the basis of the bus observability.

$$\in = f(x) = \begin{cases} 1, & if\ that\ bus\ is\ observable \\ 0 & otherwise \end{cases}$$

Consequently, row and column corresponding to PMU added bus gets deleted from connectivity matrix. If elements of visibility matrix gets 1, then system is considered to be observable [44].

A flow chart is given for the proposed methodology in fig 2.5.1

2.6 STATE ESTIMATION

2.6.1 HISTORY

Before the introduction of the SE, operators need to do the operation manually and whatsoever data they get was not that much accurate. Since the unoccasional events used to happen, accurate data needs to be taken. Methods which were used to provide the measure of the states indirectly based upon the unsynchronized power flow solution [10].

Since the data sent from SCADA to the state estimator is not adequate and inaccurate, Energy Management System (EMS) was created to preserve the system's normal conditions and make it to operate in optimum economic conditions. For this process, a series data of is needed which would be transmitted through SCADA system. Hence estimator acts as an intermediate between EMS and SCADA [30].

2.6.2 STATE ESTIMATION TECHNIQUES

It is a process of allocating the value to the unknown state variable established upon measurement from that system. This process can involves imperfect measurements which are redundant and can be eliminated using statistical criterion in order to get a true value. These values are then used to either minimize or maximize the certain objective functions [4]

If we consider the power system, state variables will be voltages and phase angles at nodes. Design of the estimators are done in such a way that they produce the best estimates of these state variables. Three well known criterion on which state estimation problem is made are maximum likelihood criterion, WLS criterion and minimum variance criterion [4].For instance, it is a mathematical tool where a set of measurements are get united with an presumed mathematical model of a system and there resultant set of equations involving measurements are fulfilled using least squares logic. Hence the states are estimated via an over determined set of equations in which of right- and left-hand sides of equations must settle with minimum squared difference[26].

Based on the timing and evolution of the estimates, it can be divided as SSE and FASE .In SSE ,all measurements are taken in one snapshot in time whereas FASE gives the recursive updating to the states in addition of the tracking changes into normal operations[18].

2.6.2.1 PROPOSED METHOD :- WEIGHTED LEAST SQUARE METHOD[6]

Description: It involves the iterative solution of Normal equations .An initial guess has been made for the state vector X^0 . For the power flow solution, initial guess is taken as flat voltage profile i.e., all bus voltages are assumed as 1.0 per unit[6].

Algorithm: -

1. Start iterations by iteration index; k = 0
2. Initialize state vector X^K, typically as flat start.
3. Calculate gain matrix, $G(X^K)$
4. Calculate right hand side $T^k = H(X^K)^T R^{-1}(Z - h(X^K))$
5. Decompose $G(X^K)$ and calculate for ΔX^K
6. Convergence test , max] ΔX^K [< €?
7. If not converges, update $X^{K+1} = X^K + \Delta X^K$, K=K+1, and go to 3rd step, else stop.

Computational data in each iteration, K are:-

1. From R.H.S. of Equation

   (a)Measurement function, $h(X^K)$

   (b)Measurement Jacobian ,$H(X^K)$
2. $G(X^K)$ and solution of Equation

   (a) Gain matrix $G(X^K)$

   (b)Decomposition of $G(X^K)$ and its Cholesky factors

   (c) Perform forward/back substitutions for solving ΔX^{K+1}

A flow chart of WLS proposed method is shown in below figure 2.6.2.1

2.6.3 NEED FOR STATE ESTIMATION WITH PMU:-

Since the conventional measurements given by SCADA are immature to capture the dynamics of system with respect to real time which cannot be done by the SE alone for the continuously changing system. Hence it is needed that the SE scheme should get modified in such a way that it should be able to handle and monitors these changes [18].

Recently developed device, PMU is a promising device as it is synchronized with the GPS universal clock. It provides direct measurement of the voltage and current of bus where it is placed. It gives sample at a higher frequency as compared to the traditional sensors used in the SCADA. Hence its measurement value are more precise and timelier based. But the problem of PMU is its placement as we cannot place it at the buses. Hence economic will the barrier for this. Therefore it will be beneficial to combine SE measurements with the PMU measurements rather to use the SE for whole system for measurement [18]. But again the problem will be seen while combining these two data as PMU based data are more in numbers and will be difficult to handle and combining them will be difficult as they have different time schedules[18][24].

Method to combine these traditional SE with PMU can be done as:-

1) Use of a single estimator in which measurements of both the methods will be there
2) Use of two-stage scheme, in which SE provided by traditional method will get improved by the PMU measurements which is the second estimator [18].

2.6.3.1 PROPOSED METHOD:-

Description: - In addition to bus voltage, PMU can also measure the current associated to the line. From the given transmission line model, the concept of the line current can be drawn to compute the voltage of the other side. Advantage of measuring the line currents is that it provides extension to the voltage measurements to those buses also where there is no PMU is installed. Using the optimal placement of the PMU, the number of PMU needed can be reduced and hence it can measure the bus voltages indirectly. Hence equation can be written as follows.

$$\begin{bmatrix} Ep \\ Eq \\ Ipq \\ Iqp \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ ypq & -ypq \\ -ypq & ypq \end{bmatrix} \begin{bmatrix} Ep \\ Eq \end{bmatrix}$$

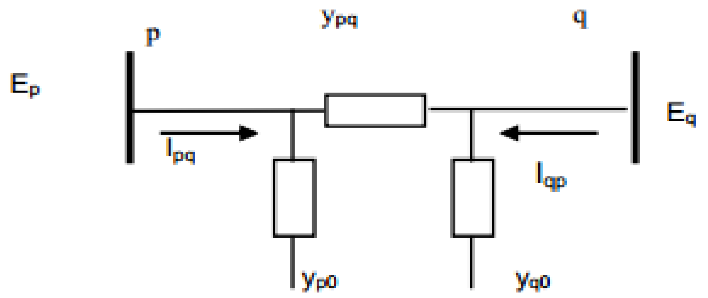

Fig 2.6.3.1: - ∏ model of transmission line[10]

FLOWCHART FOR PROPOSED METHODS :-

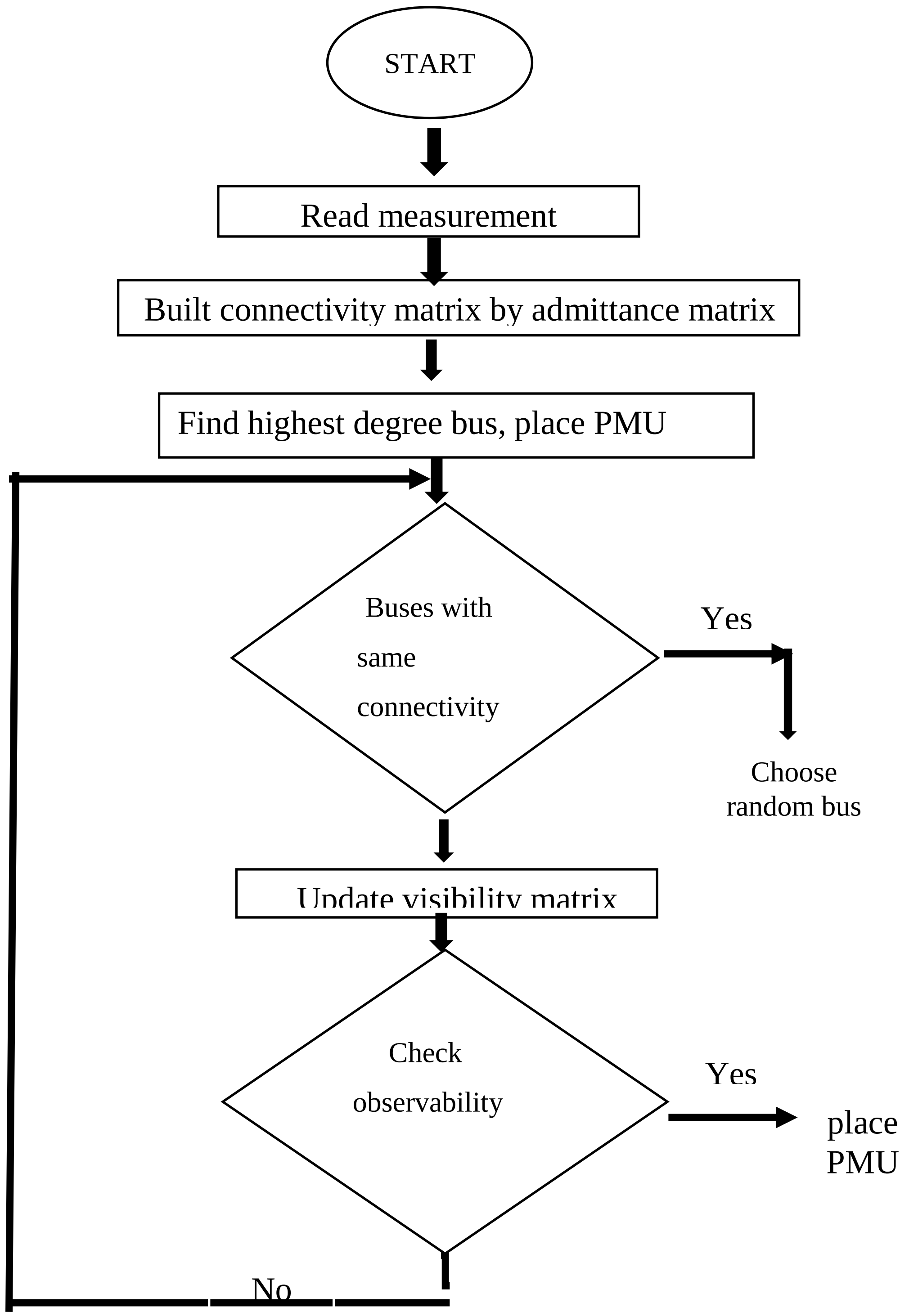

Fig 2.5.1:-Flowchart of Greedy algorithm [44]

FLOWCHART OF WLS:-

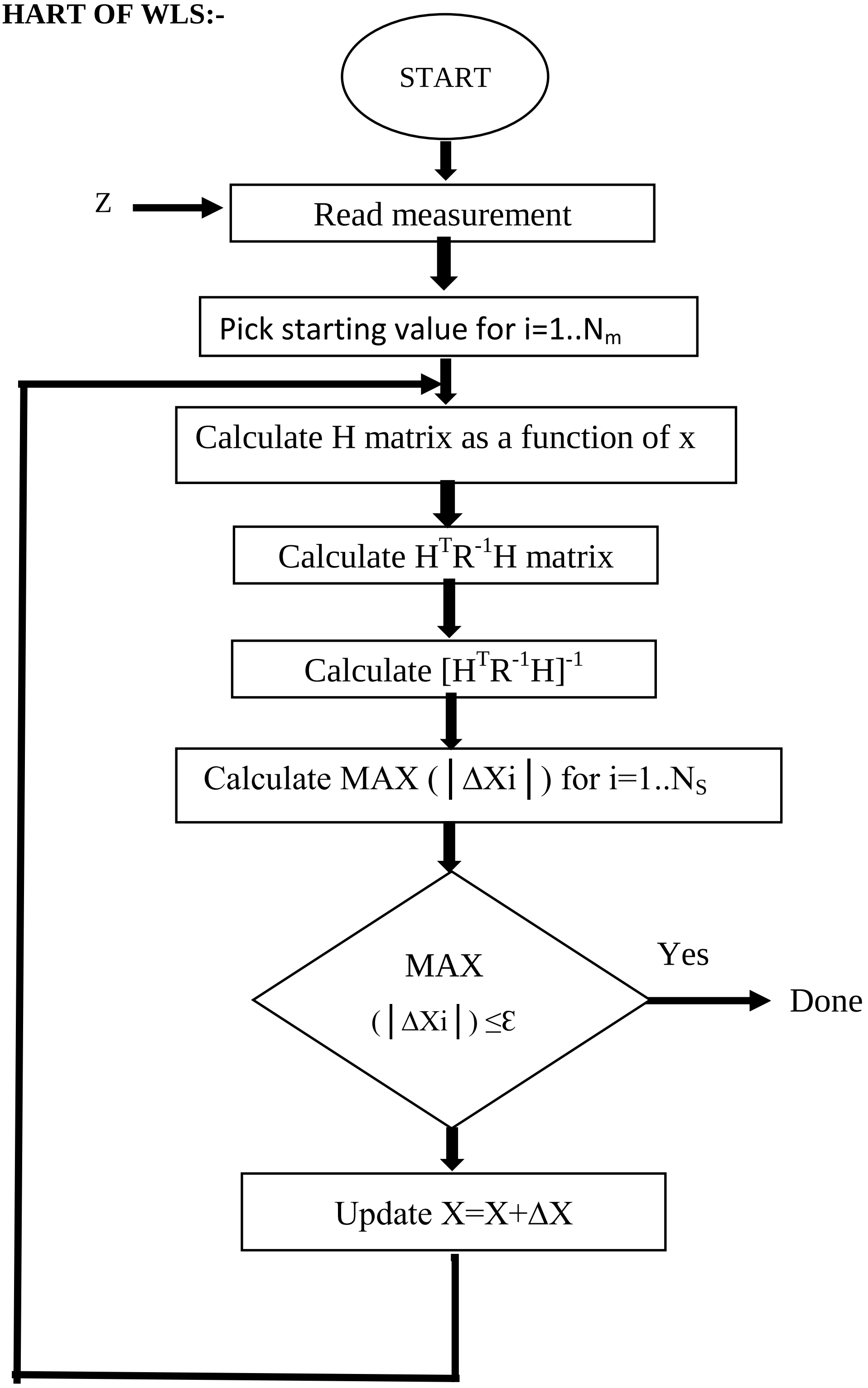

Fig 2.6.2.1: - Flowchart of WLS

CHAPTER 3
VOLTAGE STABILITY

3.1 INTRODUCTION

Voltage stability comes under the classification of power system stability. Figure 2 shows the overall view of the power system stability depicting its categories and subcategories. These classifications are done on the basis of their physical nature, size of the disturbances and the types of the devices, duration and process which are required to access these stabilities.[2]

3.2 DEFINITIONS OF VOLTAGE STABILITY

It is the ability of the power system to maintain constant voltages at all buses after being exposed to a disturbances. Some of the reasons of voltage instabilities are loss of load, unintentional tripping of elements by protective devices which leads to the cascading outages. But the main reason for instability is the load. Loss of synchronism between the generators can be seen. These causes can either increment or decrement of the voltage at the buses. Restored loads too causes the high stress on the lines .Voltage drop limits the capability of power transfers and is restricted due to the reactive power demand increase. Voltage rise happens due to the capacitive nature of the network, over voltages due to self-excited synchronous machine. These problems has been seen in the HVDC terminals also [5].Cascading outages refers to the order of events due to voltage instability consequently leads to the black out or abnormal low voltage condition sustained in the network for the longer duration. These whole process is often said as voltage collapse [2].

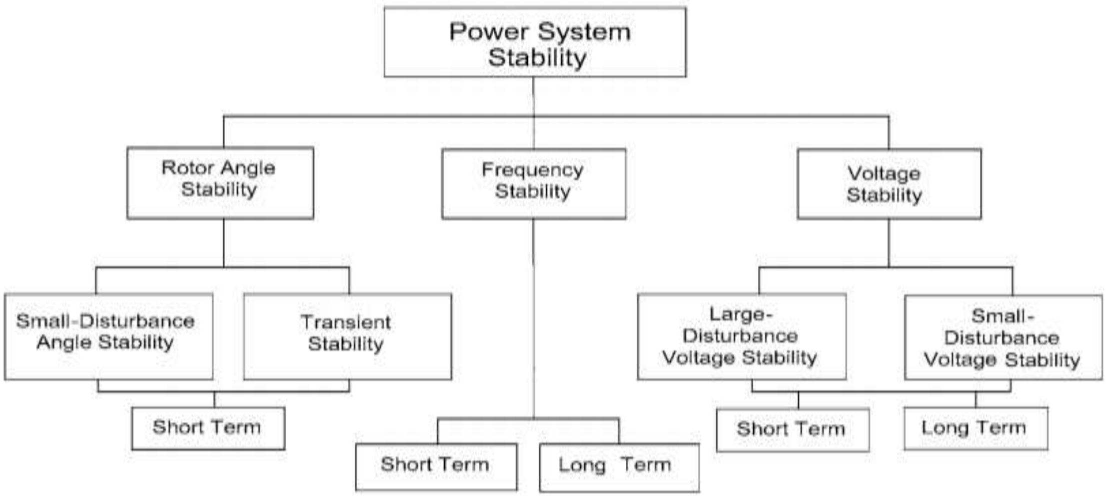

Fig 3.2.1:- Classification of power system stability [5]

3.3 CLASSIFICATIONS

It can be done either on the basis of their disturbance levels or the time duration [5].

i. Level of disturbance

S.no	Features	Large disturbance	Small disturbance
1	Definition	ability of system to be in equilibrium state (steady voltage at buses) after being subjected to large disturbance.	ability of system to be in equilibrium state (steady voltage at buses) after being subjected to small disturbance.
2	Examples	system faults, system contingencies, loss of generation etc.	Influenced by loads, continuous and discrete controls at a time instant.
3	Methods	inspection of nonlinear response of the network	suitable approximation, equations can be linearized but it will not give the effect of the nonlinear response.

Table 3.3.1 :-Voltage stability classification on the basis of disturbance.

ii. Time frame

S.no.	Features	Short-term	Long-term
1	Time span	Several seconds.	Several or many minutes.
2	Method	System's differential equations.	long-term simulations
3	Example	fast acting load such as induction motors, HVDC converters controlled loads (electronically)	slower acting component such as tap-changing transformers, , controlledloads(thermostatically)

Table 3.3.2:-Voltage stability classification on the basis of time frame.

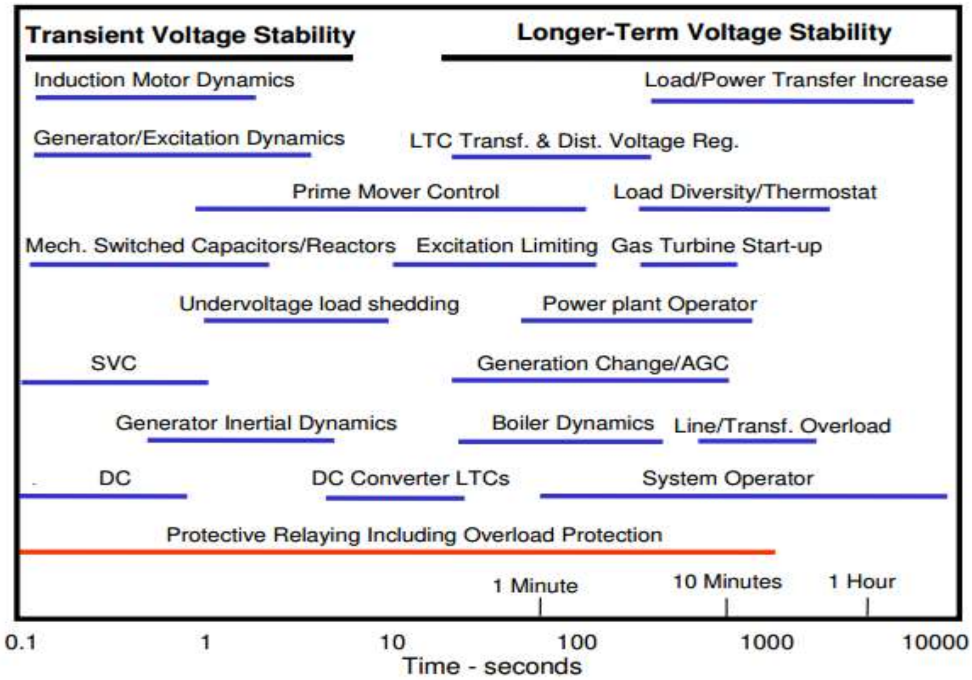

Fig 3.3.1:-Components and their controls time frame [2]

3.4 VOLTAGE STABILITY ANALYSIS TOOLS:-

1. **Power flow analysis**:-

Load flow analysis is a process to calculate the power flows and the voltages of a line for specified bus condition. It is used to examine the normal state of operation. Mathematically sets of different non -linear equation has been taken and solved by using different methods such as Guass seidel method[25], NR method and fast decoupled method. All these are iterative based methods. The nonlinear equations are due to their dependency of the load characteristics [12]. It is beneficial in terms of future expansion planning [36].

PROPOSED METHOD:-

Description:- Here, NR method has been chosen because of the fact that it has quite fast response of convergence and been used in the practical system also. After each iteration, Jacobian matrix is needed for calculation. This Jacobian matrix is also used for determining the system stability [36].

2. **PV and QV analysis** :-

PV analysis is used to find voltage stability of a radial as well as for a mesh network. Analysis will be done by selecting a candidate bus whose real power increased in a steps and thus there corresponding voltage is calculated by running the load flow program until unless the power flow does not converge. For these candidate bus, PV curve is plotted.[37]

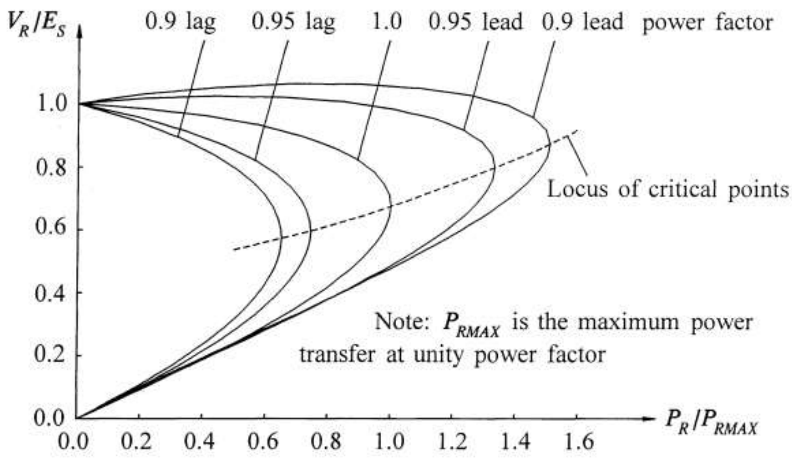

Fig 3.4.1 :-P-V curve[2]

Two solutions of voltages of load flow [12]:-

- upper voltage solution:-"+" sign ;stable
- Lower voltage solution:- "-" sign ;unstable.
- tip of "nose curve" :- critical point or maximum loading point
- Operating near the stability limit is impractical and sufficient power margin, thas to be allowed.

In QV analysis, the reactive power at candidate bus is varied in steps and its corresponding voltage is calculated and hence the curve between these values are drawn [12].

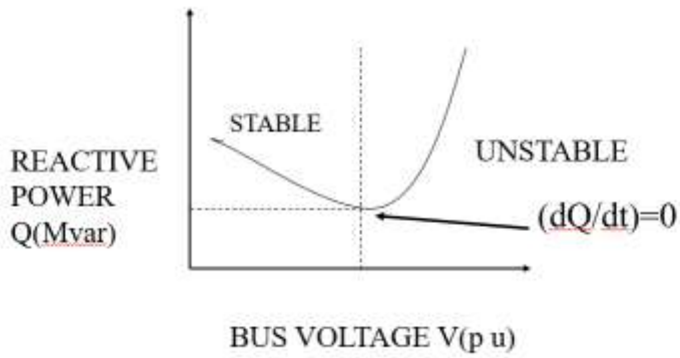

Fig 3.4.2 :-Q-V curve [2]

Voltage stability limit:-

- bottom of the curve; dQ /dV = 0
- right hand side=stable; Q & V both increases
- left hand side=unstable; Q decreases V increase [12].

PROPOSED METHOD:- Varying the load condition from 70% to 120% in a linear manner for a period of 10 time sample step. Analyze the plot of PV drawn after taking the values of varied P,V and Q by running the N-R method successively.

3. **Modal analysis**:-

Using the load flow analysis, computation of the Eigen values and their associated Eigen vectors formed from the reduced Jacobian matrix is considered [19].

Let $\Delta P=0$, then $\Delta Q= [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}] \Delta V$

$J_{R=} = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}]$ =reduced Jacobian matrix

It gives the correlation between the V magnitude and Q injection of the bus. Calculation of Eigen values are done from this matrix. If the Eigen values are positive then the system is stable else unstable even if one of them is negative. If Eigen value comes out to be a zero it implies that the system is on the margin. Calculation of minimum Eigen is done to measure the voltage collapse situation. For obtaining the weakest bus, bus participation factor is calculated. From the reduced Jacobian matrix, left and right Eigen vectors are also calculated [8].

4. **Voltage Stability Indices** [39][8]

Several voltage stability indices are there for the calculation of the voltage stability and are discussed in literature survey in [8] and [39]. Even the PMU measurements can be helpful in determining the voltage stability margin [42].It will provide a precise knowledge of deviation of the operating point from voltage stability limit. Hence to calculate it, VSI plays an important role for the system operator. These indices are the indicators of the proximity of the instability. These indices values ranges from 0 to 1 for no load to voltage collapse [8]. They will the reveal the critical bus or the stability of lines connected between the buses. If the bus is found to be in critical state then certain corrective measures has to be taken such as use of series, shunt capacitor and synchronous condenser [37].

3.4.1 PROPOSED INDICES :-

Description of the some of the used indices are given below:-

a) V/V0 index: - Here the V is to bus voltage obtained from the load flow and V0 is new voltage obtained from the load flow while keeping all loads to be zero. There ratio will give the effective detection of weak buses.
b) Line Stability Index, Lmn:-It can be derived from power transmission concept used in a single line where the voltage quadratic equation's discriminant is made to greater than zero for stable operating condition. If the value of the discriminant comes out to be lesser than zero then the system will be unstable.
c) Line Stability Index, FVSI: - Concept is same as that of used in Lmn but varies in its formula.
d) Line Stability Index, LQP: - Concept is same as that of used in Lmn but varies in its formula.
e) Line Stability Indices, VCPI: - They uses the concept of maximum power transferred through a line.

Mathematical approach for VSI can be done from the figure below which represents the power line model.

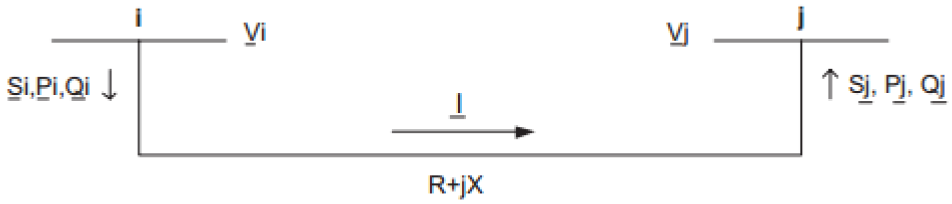

Fig 3.4.3:- Power Line Model [8]

Here symbol "i" denotes sending bus s while "j" denotes the receiving bus r. Some of the notations other than this used in the formulas are describes below:-

Z = line impedance

X = line reactance

Qj = reactive power at receiving end

Vi = sending end voltage

Θ= line impedance angle, and

δ = angle difference between the supply voltage and the receiving voltage.

Pi = real power at the sending end

Pr (max) and Qr (max) = maximum active and reactive power

Ploss (max) and Qloss (max) = real and reactive loss.

a*L* and a *G* = set of load and generator buses respectively.

Vi and Vj =voltage phasors

Elements of Fji are calculated from the [Y] bus matrix for the network.

S.NO.	NAME OF INDICES	FORMULA	CONDITION FOR STABLE/UNSTABLE
1.	Fast Line Stability Index [FVSI]	$FVSI_{ij} = (4Z^2 Q_j)/ V_i^2 X$	Index value close to 1 , most critical line of the bus.
2.	Line stability index [L_{mn}]	$Lmn = (4 Q_j X)/(V_i \sin(\theta-\delta))^2$	Must be less than 1.00 to have stable system.
3.	Line Stability Factor [LQP]	$LQP = 4(X/ V_i^2)[(X/ V_i^2) P_i^2 + Q_j]$	Must be kept lower than 1.00 to maintain a stable system.
4.	Voltage Collapse Proximity Index [VCPI]	VCPI(power)= Pr/Prmax = Qr/Qrmax VCPI(loss)= Ploss/ Ploss(max) = Qloss/ Qloss(max)	Vary from 0 (no load condition) to 1 (voltage collapse).

Table 3.4.1: Voltage Stability Indices [8]

CHAPTER 4

REVIEW OF LITERATURE

4.1.Phasor measurement unit:-

Phadke,A.G.,et.al.[9](2006) describes the history of PMU and enumerated their commercial availability which was done in early 1990's. Earlier only the theoretical use was established in protection and control .However usage was limited in digital system disturbance recorders (DSDRs).
De La Ree, Jaime, et al.[13](2010) discusses the PMU and WAMS technology in a very brief manner and its potential application in the fields of monitoring control and protection.

Manousakis, N. M.,et.al.[14](2011)Author has given the literature review on OPP problem needed for the complete observability of the network using the minimal set of PMUs. He has considered the metaheuristic,heuristic and mathematical programming for this OPP.

Singh, Bindeshwar, et al.[17](2011) has discussed the several application of PMU with fact controller indicating their current status in power system which will be helpful in drawing the attention towards this application of PMU.

Manousakis,et.al.[22] (2012)addressed the different state of art for OPP of PMU discussing several conventional ,heuristic and meta heuristic techniques which will be helpful in future application by providing the full observability of the network.

Sexauer,et.al.[27](2013) discussed the need of PMU in the distribution side needed for the study of the dynamic state and control. It shows that the PMU based measurement forms the new phasor data which is more advanced than the traditional grid method data.It also shows the potential applications of PMU in Distribution Management system.

Hany A. et.al.[31](2014) give the distribution network reconfiguration where problem of OPP for full observability is carried out using the ant colony optimization (ACO) algorithm to solve the minimum losses problem. For optimal minimum no. of PMUs placement they uses Greedy algorithm as an optimization tool on 33-node distribution system. Moreover in addition to this they improves the power loss, node voltages with the help of PV energy and wind energy.

S. L. Ramírez-P and C. A. Lozano[41] (2016) gives the review and comparison of all the methods of optimal placement of PMU for voltage stability assessment. Methods are as follows:-Tabu Search, Simulated Annealing and Genetic Algorithms ,Heuristic algorithm, theoretical and graphical method, linearized power system state estimator model with the help of augmented incidence matrix, sensitivity-constrained methods, two-stage method, binary optimization of particle swarm (BPSO) are some of the methods where author has given the review about how this methods are used in the system for complete observability .Review on state estimation techniques are there and its pros and cons ;method includes Singular Value Decomposition (SVD), the random fuzzy variables (RFVs) and the Monte Carlo method are also described for finding out the state variable's uncertainties. Voltage stability are also given with the help of several voltage stability load index (VSLI). IEEE-39 test bus system is used.

Chouhan, Dolly,et.al. [43] (2016) has described the various optimal placement techniques of PMU and discusses about the voltage stability.

Jaiswal, Varsha, et.al.[44](2016) proposes a new technique for SE in electric power systems where the optimal placement of PMU is done using the greedy algorithm and then the state estimation technique has been used.to check the efficient performance of the method, it is being used on the IEEE test case of 5,14,30,57,118 test bus system.

4.2 Voltage stability :-

Kundur, Prabha, et al. [5] (2004) has addressed report in which power system stability has been defined more specifically, a well-organized basis for its classification is given and discussed some of the associations related to issues like reliability and security.

Reis, Claudia, et.al.[8](2006) described the various voltage stability indices and there comparative analysis. IEEE 14 bus test system verifies the effectiveness of these indices under varying load condition.

James A. Momoh,et.al[11](2008) have given the real time PMU application for voltage stability which will have computation and controls of devices. By this we can also ensure the voltage instability on its occurrence. 30-bus test system is used. In this, voltage stability margin used as the constraint and its violation will be concluded as the voltage collapse state which can be deduced from Voltage stability index. It will also tells the improvement of voltage profile. Weak node points and different loading conditions are also taken into the account.

Doig Cardet, Christine Elizabeth[12] (2010) addressed the performance of various VSI and were tested on a 5-bus system and on a 39-bus system.

Shirisha, S., et.al.[19] (2012) has proposed an algorithm which is a combination of Artificial Immune system clonal selection algorithm and modal analysis. Modal analysis will be used to evaluate the Eigen values and their respective participation factors respectively.

S. Kesherwani, et.al. [20](2012) presented completely observable system with the help of topological observability method so as to calculate the minimum no. of PMUs. method whose placement are done using the conventional method and injection method full observability. Data collected from them are in real time current and voltage phasors which is for finding out the L –index needed to assess the voltage stability in between the points of normal as well as the instable operating point. Simulation is done 0n IEEE-14 bus and binary integer programming method is used.

Xiaoming Mou,et.al. [21](2012) have tried to do that they have taken IEEE-30 bus system for checking out their simulation result. Here they have taken few buses with heavy loads on it and calculated that those few buses will have the impact on the voltage profile of the system .For this they have chosen analytical index method both for online assessment of voltage stability and for optimal placement of PMU overcoming the cons of use of thevenin model method. Here it is shown how the impedance ratio will varies with the scaling factor and when it comes to or nearer to unity,a state of voltage collapse has been deducted with the increase in the scaling factor.

Gautam, Lalit Kumar,et.al.[36] (2015) has discussed the power flow analysis method using NR-method and calculated the voltage stability indicator.

THAKUR, NEHA et.al.[37] (2015) has used basic static voltage stability tools i.e., PV and QV curve for analysis purpose and finds the relationship of P and Q variation with the change in V at a selected bus.

A.S.Telang, et.al.[39] (2015) describes the various voltage stability indices and there comparative analysis. IEEE 14 bus test system check the effectiveness of these indices under varying load condition in addition of use of line VSI to predict voltage collapse .

A.c. Adewole and R. Tzoneva [33](2015) have tested the component of the PMU using digital simulator used in real time and have concluded the voltage stability margin by VSI mainly generator derived indices. Test system was New England 39.

In [35](2015),the authors have chosen a new procedure for voltage stability monitoring which provides the faster and accurate results namely Artificial Neural Network (ANN).Here the feature of reduction is most advantageous as it will not only reduces the feature requirement but also the associated system quantities will get lowers down. Using voltage stability indicator, load shedding also be implemented. Using thevenin equivalent circuit several indices like Power Transfer Stability Index ,Power based Voltage Stability Margin and Line(L) index so on are calculated. Then the concept of ANN is applied based on its feature reduction and feature selection methods. Based on the results whether to do load shedding or not is also described which is again based on the indices method used which tells us the amount of load to be taken out and from which bus also.

4.3 State estimation:-

Zivanovic, R,et.al.[3] (1996) performs simulation on IEEE14 bus system using PMU measurements in the SE and found an increase in the confidence of the state estimation result. He showed the possibility of coexisting of new linear SE algorithm and existing non-linear estimator

Huang, Yih-Fang, et al.[18] (2012) presented state estimation at the transmission level and distribution level including its history and shows the need for the research and innovativeness to provide the measure to account the new challenges of the future grid. Here some examples has also been presented using signal processing.

Yang, Peng, et al.[24] (2013) introduces a model for SE using PMUs with phase mismatch. They had used the numerical examples to show the improved accuracy of algorithms when imperfect synchronization is taken into account.

Gomez-Exposito, Antonio, et al. [16](2011) presented the benefits of both future and existing State Estimators (SE) which can be achieved by integrating PMU in real monitoring Also presented a review of the PMU's technological aspects, its potential application and its deployment issues in addition of the alternative SE formulations in presence of PMUs .

Li, Qiao,et.al.[15](2011) presented the OPP of PMU using greedy algorithm in which the optimal experimental design is is NP-hard.Here the submodularity design criteria is there for good approximation ratio. Using greedy algorithm 63% of the optimal reduction is obtained in total variance.

Haughton,et.al.[40](2013) presents a linear, three-phase, distribution class SE algorithm which uses complex variable formulation for incorporation of PMU with distribution SE. Unbalanced single-phase cases and three-phase cases are accommodated. He also discussed about the applications in management and smart distribution system control.

R.Sudha, et.al. [23] (2012) showed optimal placement of PMU to get the data for state estimation ,improves the reliability of the system ,performs the analysis of voltage stability using indices-FVSI and LQP. Here the results of voltage and phase angle for IEEE-14 test system are then compared in two conditions i.e; with or without the PMU algorithms; WLS and LAV along with their algorithms where LAV proved to be good and inclusion of PMU leads to the error reduction. For reducing the no. of PMU needed, Zero injection busses are considered.

Zhou , Ning, et al.[34](2015) performs the comparative analysis of four Bayesian-based filtering approaches i.e. ensemble Kalman filter ,extended Kalman filter, particle filter and unscented Kalman filter, has been done using Monte Carlo methods .This approach is being used for estimating dynamic states related to synchronous machine with the help PMU. Their outcome are compared on the basis of their robustness against noise, sensitivity towards interval of samples ,process computation time .

CHAPTER 5

OBJECTIVES OF STUDY

In this thesis, IEEE 14 bus test model is used for the analysis of the voltage stability and for power system state estimation. Addition of the data monitored by PMU to the conventional measurement are also considered. Prime focus has been given to the state variable voltage. A reliable estimate of the states is crucial for all the applications done by using the state estimation. Due to the presence of disturbances and contingencies in the power system, voltage gets deviate from their operating limit and henceforth needed to stabilize the voltage in order to bring the system in equilibrium state.

The main objective of this research are as follows:-

- To gain the brief knowledge of the voltage stability
- To implement WLS technique and estimate the parameter
- To improve the performance of the state estimation by incorporating PMU measurements
- To deduce the optimal placement of PMU
- To implement these methods on the above said IEEE bus system.

CHAPTER 6

RESEARCH METHODOLOGY

A MATLAB program is performed on standard IEEE 14 test bus system data input [46] using MATLAB R/2015a software. The system has 5 generator bus bars, 20 interconnected branches and 9 load bus bars.

Description:- For a 14 bus system, 2n-1=27 where n=number of buses, then 27 state variables are needed to be evaluated. Bus 1 is chosen to be a slack bus, buses 2,3,6 and 8 are generator connected buses, refer to it as PV bus and left buses i.e.,4,5,7 and 9 are the load buses. There are 20 interconnected branches , 40 line power flows with 26 bus power flows(each P and Q are of order 13) .Refer Appendix A for line data and bus data details.

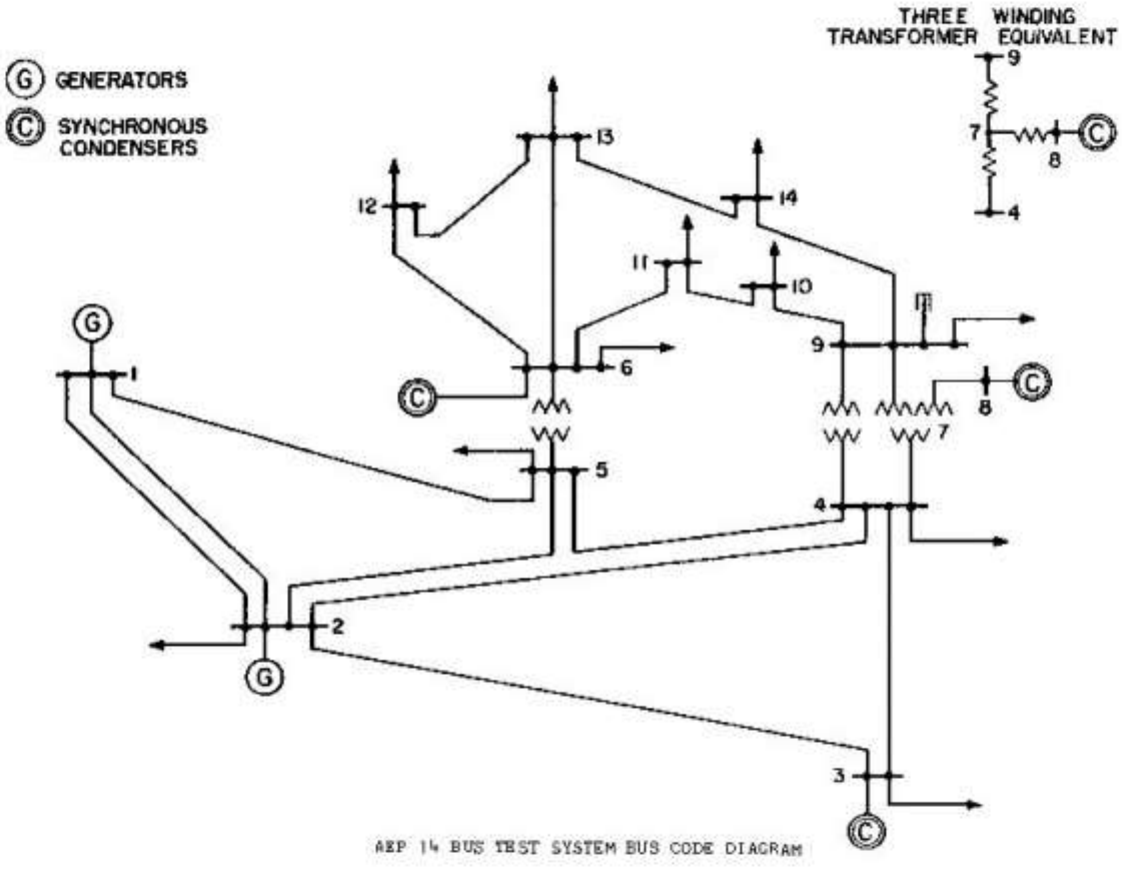

Fig 6.1 : - IEEE 14 test bus system [46]

6.1.Power flow solutions are obtained from the Newton Raphson method.

6.2.On the basis of different variable load condition where load is varied from 70% to 120% obtain the results. Samples for these variation is taken to be as 10.

6.3.Note the different values of varied active and reactive power with respect to the changed voltage.

6.4.Optimal placement of the PMU is done by the Greedy algorithm for IEEE 5,14,30,57,118 buses [44].

Computational procedure [44]: - Steps to be followed

a) Read available data
b) Using bus admittance matrix, built connectivity matrix
c) Deduce the highest degree of bus, choose that bus to be a location of PMU.
d) If two or more buses has the same connectivity, randomly picks a bus and place PMU to that bus.
e) Update visibility matrix. Check the observability of the bus. If not observable, then repeat steps c else the outcome bus is the only location of that PMU.

6.5.Perform the SE using WLS method [6]

Computational method: -

a. Collect the data of the PMU placed bus and give it as input to the state estimator.
b. Perform SE
c. Print results.

6.6.Combining the direct PMU measurement and SE measurements together [10].

Computational procedure:-

a. Let m=no. of current measurement
   q=no. of buses
   p=no. of buses having voltage measurements
b. Compute the current incidence matrix A of m ×q dimension.
c. Calculate diagonal of admittance matrix of m ×m dimension.
d. Add the shunt branches for every pi section to the diagonal matrix.
e. Obtain the measurement vector composed of p and m, represented as

$$Z= \begin{bmatrix} \Pi \\ yA + y_s \end{bmatrix} [E_b] = BE_b$$

Where ∏ is the unit matrix from which missing bus voltage rows are removed.

f. Calculate the estimator $x^{\wedge}=(B^TW^{-1}B)^{-1}BTW^{-1}Z=MZ$

Advantage of the above equation will be that it makes the estimator linear in sense that matrix M will take the measurement and convert it directly into the state estimator. It is not like early estimator which will produce nonlinear estimates[10].

6.7. On the basis of the normal state and variable loading condition, voltage stability indices i.e**.; V/V0, Lmn, FVSI, VCI** are calculated for those buses where the PMU is placed.

Description: - VSI plays an important role to determine the system's condition whether the system lies on stable case or in the unstable case. These indices and there formulation has been discussed in the Chapter 1 under subsection voltage stability analysis tools.

6.8. Comparison of these indices for the normal and different load variations are compared for IEEE 14 bus system

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Running load flow program using Newton Raphson, active and reactive power of power flow with voltage and its angle are given in tabular form. Results of the following load flow is assumed to be accurate.

Bus no.	Voltage (V)	Angle(del)	P_{LOAD}(MW)	Q_{LOAD}(MVar)
1	1.0600	0.0	0.0	0.0
2	1.0450	-4.9891	0.942	0.127
3	1.0100	-12.7492	0.478	0.190
4	10132	-10.2420	0.076	-0.039
5	1.0166	-8.7601	0.112	0.016
6	1.0700	-14.4469	0.0	0.075
7	1.0457	-13.2368	0.0	0.0
8	1.0800	-13.2368	0.295	0.0
9	1.0305	-14.8201	0.090	0.166
10	1.0299	-15.0360	0.035	0.058
11	1.0461	-14.8581	0.061	0.018
12	1.0533	-15.2973	0.035	0.016
13	1.0466	-15.3313	0.061	0.053
14	1.0193	-16.0717	0.0	0.149

Table 7.1: - Power flow solution using NR method.

8.2. Using the computational procedure of Greedy algorithm, following results has been found. In addition to the IEEE 14 bus system, reliability of this method has been carried out on different test system i.e., IEEE 5,30,57 and 118. For IEEE 14 bus system , 4^{th} bus has the highest connectivity and is connected with 2,3,4,7,5,9 buses. Therefore on placing the PMU at 4^{th} bus makes these observable. Similarly 6^{th} bus has the next highest connectivity and placing PMU at this buses makes the 5,6,11,13,12 buses observable. Process gets repeated till the entire system becomes observable. Hence the PMU are placed at 4,6,2,9,7 buses for complete observability. Moreover it shows that it is not needed to place the PMU at all the 14 buses, placing at five buses only can gives the result. Thus it proves to be an effective method for placement of PMU. Results are shown in the tabular form.

S.NO.	IEEE bus system	Total no. of PMU used	PMU placed at
1	5	1	2
2	14	5	4,6,2,9,7
3	30	11	6,10,12,27,2,15,24,3,19,9,25
4	57	21	9,13,38,14,41,6,15,24,29,32,36,56,19,21,27,30,39,46,50,53
5	118	40	50,100,13,80,18,38,60,1,6,33,85,92,105,16,57,63,66,70,77,96,110,20,24,28,31,41,47,2,10,22,30,35,45,52,54,69,71,75,89,86

Table 7.2: - OPP of PMU on different IEEE buses.

7.3. Under the variable load condition, plot of active power and voltage variation has been drawn. It can be concluded that as the load increases from 70% to 120% in the 10 steps at all buses power corresponding to this load variation cases decreases. Step size corresponds to 0.05. One of the PMU placed bus, bus 4 has been chosen as the candidate bus to perform the result due to the fact that its a load bus.

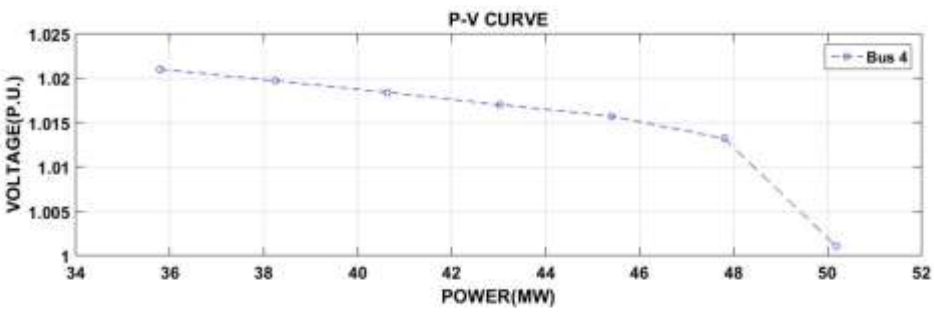

Fig 7.3.1:- P-V curve

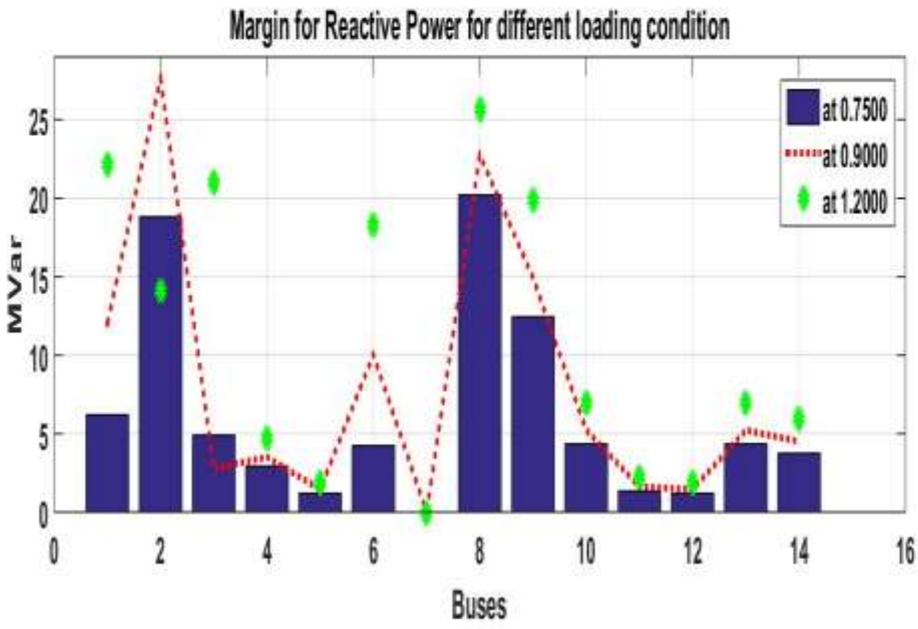

Fig 7.3.2.:- Margin of Reactive Power

For estimating the MVar margin at the all buses under different load variation conditions, a graph is drawn. From this graph, we can deduce which bus will show demand of reactive power before the system undergoes to voltage collapse. Considering the PMU placed buses 2,4,6,7 and 9 under the different load condition at 0.750, 0.900 and the 1.200. It has been found that in all these variable load, bus 7 has the lowest MVar of Q indicating this bus to be a critical bus. Bus 2 has the sufficient MVar margin throughout this load variation. Apart from bus 7, buses 5,11 and 12 also considered to be the critical line.

7.4. WLS performance for SE.

Bus No.	Base V	Base del	Measured V	Measured Del
1	1.0600	0	1.0068	0.0000
2	1.0450	-4.9891	0.9899	-5.5265
3	1.0100	-12.7492	0.9518	-14.2039
4	1.0132	-10.2420	0.9579	-11.4146
5	1.0166	-8.7601	0.9615	-9.7583
6	1.0700	-14.4469	1.0185	-16.0798
7	1.0457	-13.2368	0.9919	-14.7510
8	1.0800	-13.2368	1.0287	-14.7500
9	1.0305	-14.8201	0.9763	-16.5125
11	1.0461	-14.8581	0.9758	-16.7476
12	1.0533	-15.2973	0.9932	-16.5397
13	1.0466	-15.3313	1.0009	-17.0203
14	1.0193	-16.0717	0.9647	-17.8967

Table 7.4. Comparison of parameters of NR and WLS method

Using this for statistical approach ,reduces the uncertainty level and has good accuracy level with less computational time. But increasing the buses will cause the iteration to get increased. More the iteration, more will be the computational time is needed.

7.6. Proposed algorithm performance of adding direct measurement of PMU and using the extension of line current to sense the adjacent bus voltages. Matrix M is a conversion matrix which takes the measurement of voltage and current and provides a linear estimate. No long iteration method is there and hence it has fast computational time. As long as the system remains to be intact conditions will get satisfied. Estimation x has the same concept that of the traditional method of SE uses to find the estimate.

```
B=[gg;y_comp];            % generate measurement vector
I_comp= y_comp* V;                   %Deducing current
M= inv(B'* inv(W) *B)*B'*inv (W)     % conversion matrix
x= inv(B'* inv(W) *B)*B'*inv (W)* B_v
```

Since we have taken NR calculated values of voltage to be accurate and standard. This estimate provides the same result as that of NR showing its successful implementation on IEEE 14 test bus. Result of

>> x=

1.0600

1.0450

1.0100

1.0132

1.0166

1.0700

1.0457

1.0800

1.0305

1.0461

1.0533

1.0466

1.0193

7.7. Calculation of the various indices has been done on the PMU placed buses.

a) V/V0:-

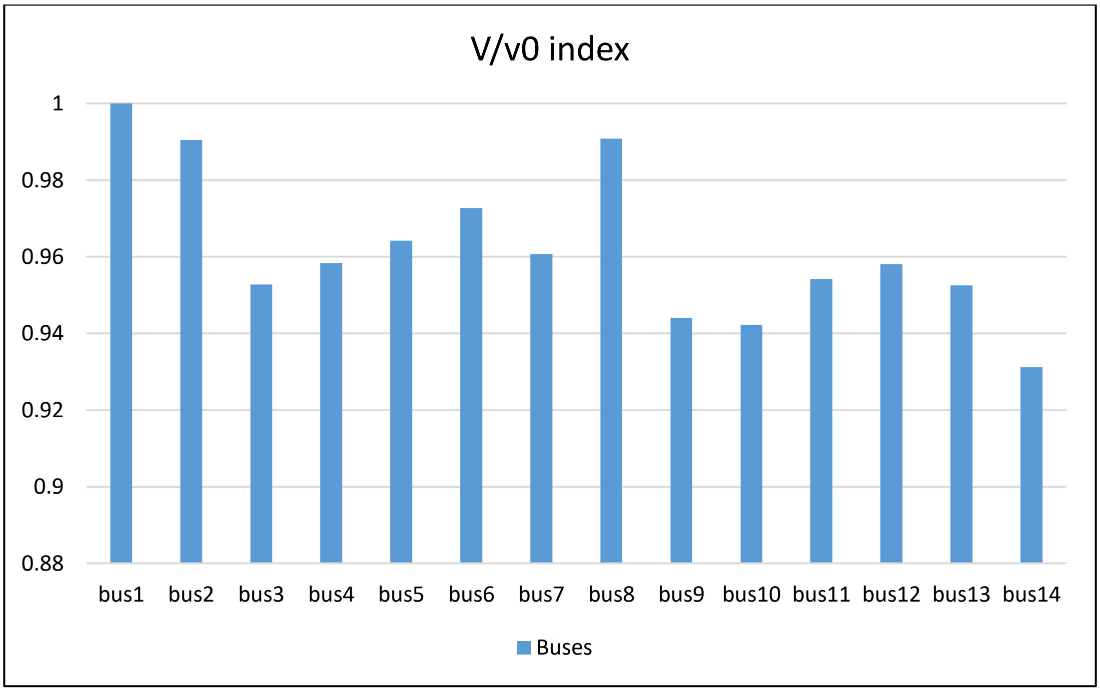

Fig 7.7.1.: - V/v0 index

From V/V0, bus 1,2 and 8 are found to be critical buses as they have index falling more to 1.

b) FVSI and Lmn index:- Analyzing the table 8.7.1, as the load variation increase from 0.70 to 1.20,the index values also increases at each buses. At the extreme load level, bus 8 has found to be critical bus as its near to 1. Moreover the value of both the indices comes out to be the same. These variables have the dependency on reactive power.

BUS	**LOADING**		
	0.70	**0.90**	**1.200**
1	0.1271	0.3711	0.6832
2	0.5178	0.8849	0.4710
3	0.2532	0.0949	0.7531
4	0.0917	0.1191	0.1686
5	0.0373	0.0485	0.0683
6	0.0776	0.3245	0.6254
7	2.2979e-14	5.8044e-15	0
8	0.5913	0.6943	0.8288
9	0.3864	0.5050	0.7306
10	0.1357	0.1774	0.2569
11	0.0416	0.0541	0.0775
12	0.0370	0.0479	0.0684
13	0.1350	0.1752	0.2514
14	0.1192	0.1565	0.2289

Table 7.7.1:- FVSI and Lmn Results

c) LQP index:- Same conclusion is valid here also that loading increases the index values at each bus.At extreme load condition bus 2 comes out to a critical bus.

BUS	**LOADING**		
	0.70	**0.90**	**1.200**
1	0.5435	0.9112	1.0274
2	0.0355	0.0605	0.0399
3	0.1025	0.1987	0.4135
4	0.0340	0.0552	0.1060
5	0.0015	0.0016	0.0014
6	0.0062	0.0221	0.0406
7	1.3932e-15	3.4831e-16	4.1982e-32
8	0.0380	0.0446	0.0504
9	0.0121	0.0110	8.5411e-04
10	0.0070	0.0085	0.0100
11	0.0023	0.0029	0.0037
12	0.0017	0.0021	0.0022
13	0.0057	0.0065	0.0059
14	0.0040	0.0039	0.0012

Table 7.7.2. LQP results

d) VCPI index :- Calculation is done taking the maximum power transfer capability of line to find the index. Analysing the results of table 7.7.3 at 0.70 loading , bus1 is the critical line and as the load increases bus 1 is only found be the critical but not much critical. Its value lies in between 0-1. This index value corresponds to the active power.

BUS	**LOADING**		
	0.70	**0.90**	**1.200**
1	0.8525	0.6934	0.4238
2	0.0220	0. 0230	0.0405
3	0.4293	0.2447	0.1881
4	0.0948	0.1176	0.1548
5	0.0201	0.0271	0.0411
6	0.0219	0.0204	0.0229
7	4.5897e-17	8.3472e-17	1.3918e-16
8	0	0	0
9	0.0711	0.0729	0.0802
10	0.0388	0.0913	0.0730
11	0.0093	0.0126	0.0198
12	0.0160	0.0214	0.0329
13	0.0574	0.1273	0.1124
14	0.0580	0.1061	0.1701

Table 7.7.3 VCPI (P)

Referring the table 7.7.4.VCPI (Q) index referred to maximum reactive power ,as the loading increases criticality of the lines is maintained to be in between 0 and 1.

BUS	LOADING		
	0.70	**0.90**	**1.200**
1	0.0102	0.0144	0.0127
2	0.0770	0.1332	0.0732
3	0.0914	0.9792	0.1221
4	0.0157	0.0230	0.0485
5	0.0055	0.0071	0.0101
6	0.0114	0.0479	0.0934
7	3.3484e-15	8.4578e-16	0
8	0.0862	0.1012	0.1208
9	0.0595	0.0811	0.1322
10	0.0199	0.0261	0.0381
11	0.0061	0.0079	0.0113
12	0.0054	0.0070	0.0100
13	0.0199	0.0260	0.0381
14	0.0176	0.0234	0.0352

Table 7.7.4:- VCPI(Q)

If the bus is found to be in critical state then certain corrective measures has to be taken such as use of series, shunt capacitor and synchronous condenser [37]. From table 7.7.5 to 7.7.7 comparative analysis of indices on different buses for different load cases has been shown. Indices result are between 0 to 1. Buses with index value 1 or nearer to it are considered to be critical bus and to retain the system back to its normal condition, corrective measures should be taken.

Indices/ Loading	0.70	0.90	1.200
FVSI	0.5178	0.8849	0.4710
Lmn	0.5178	0.8849	0.4710
L_{QP}	0.0355	0.0605	0.0399
VCPI(1)	0.0220	0. 0230	0.0405
VCPI(2)	0.0770	0.1332	0.0732

Table 7.7.5 Comparison of indices on Bus 2

Indices/ Loading	0.70	0.90	1.200
FVSI	0.0917	0.1191	0.1686
Lmn	0.0917	0.1191	0.1686
L_{QP}	0.0340	0.0552	0.1060
VCPI(1)	0.0948	0.1176	0.1548
VCPI(2)	0.0157	0.0230	0.0485

Table 7.7.6 Comparison of indices on Bus 4

Indices/ Loading	0.70	0.90	1.200
FVSI	0.0776	0.3245	0.6254
Lmn	0.0776	0.3245	0.6254
L_{QP}	0.0062	0.0221	0.0406
VCPI(1)	0.0219	0.0204	0.0229
VCPI(2)	0.0114	0.0479	0.0934

Table 7.7.7: - Comparison of indices on Bus 6

Thus it can be concluded that VSI values will be higher at the maximum loading condition and that bus will be referred to be as the critical lines.

CHAPTER 8

CONCLUSION AND FUTURE SCOPE

8.1 CONCLUSION

Power system is highly dynamic in nature and due to the emerging uncertain conditions i.e. contingencies and disturbances, state variables gets deviate from there operating condition thus causes instability. To evaluate this state variables effectively and in robust manner, State Estimation process is carried out for best estimate of the state. State estimation plays an important role in abnormal condition detection, contingency analysis and so on. But in traditional evaluation method, state and its measurement set corresponds to a particular time are provided followed by a heavy computation and nonlinear iteration which are not possible to get evaluated in the short time of interval. This problem is overcome by deploying Phasor Measurement Unit for wide area monitoring. Due to fact that it is GPS synchronized, it provides data more frequently and direct measurement of the bus in terms of voltage and current with high speed and accuracy. But in practice, it will be more uneconomical to place the PMU at each and every bus. Therefore optimal placement of PMU is done so as to make the system complete observable.

In this dissertation, state variable voltage has been chosen for understanding the stability. IEEE 14 bus test system is used for analysis purpose on MATLAB R/2015a software. Under the varying load condition, P-V curve and reactive margin with buses curve are drawn which shows that there is a decrease in the power as load increases and the bus with the lowest reactive margin is considered as the critical buses. Voltage Stability indices has played an important role in finding out voltage collapse condition. Indices V/V0, Lmn, VCI, FVSI and VCPI has been calculated for the PMU placed buses under varying load condition. For finding out the placement location for the PMU, OPP of PMU is met by using Greedy algorithm. This algorithm finds the bus with the maximum connectivity for placement of PMU. Indices values lies between the 0 (normal condition) to 1(voltage collapse) showing the criticality of the buses. State estimation has been performed using the WLS method which is based on the nonlinear iterative method. Considering its nonlinear estimate, proposed method of using direct measurement of PMU with SE makes the linear estimate which does not need any iterative method. It forms a matrix that takes the direct measurement of states and calculates its linear estimate. It not only provides the voltage of the located bus but also helps in indirect calculation of the adjacent bus by the means of using the line currents.

8.2 FUTURE SCOPE

This dissertation mainly focuses on the voltage stability using voltage stability indices calculation under normal load and load variation case and other analysis tools such as P-V curve, Q-V and Eigen value method and finally the use of PMU with SE for linear estimation with its optimal placement technique. Further investigation can be made on proposed scheme as follows:-

a) Testing it on more complex system.
b) Testing for ill conditions system
c) Finding more better techniques for optimal placement
d) Use of measurements other than the voltage for state estimation
e) Developing a dynamic state estimator for fast process which should be able to get completely synchronized with PMU.

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APPENDIX

A) IEEE 14-Bus system statics

A.1 Line data

Bus	Type	V_{SP}	theta	P_{Gi}	Q_{Gi}	P_{Li}	Q_{Li}	Q_{MIN}	Q_{MAX}
1	1	1.060	0	0	0	0	0	0	0
2	2	1.045	0	40	42.4	21.7	12.7	-40	50
3	2	1.010	0	0	23.4	94.2	19.0	0	40
4	3	1.0	0	0	0	47.8	-3.9	0	0
5	3	1.0	0	0	0	7.6	1.6	0	0
6	2	1.070	0	0	12.2	11.2	7.5	-6	24
7	3	1.0	0	0	0	0.0	0.0	0	0
8	2	1.090	0	0	17.4	0	0.0	-6	24
9	3	1	0	0	0	29.5	16.6	0	0
10	3	1	0	0	0	9.0	5.8	0	0
11	3	1	0	0	0	3.5	1.8	0	0
12	3	1	0	0	0	6.1	1.6	0	0
13	3	1	0	0	0	13.5	5.8	0	0
14	3	1	0	0	0	14.9	5.0	0	0

A.2. Bus data

From bus	To bus	Rp.u.	Xp.u.	B/2 p.u.	Tap ratio
1	2	0.01938	0.05917	0.0264	1
1	5	0.05403	0.22304	0.0246	1
2	3	0.04699	0.19797	0.0219	1
2	4	0.09811	0.17632	0.0170	1
2	5	0.05695	0.17388	0.0173	1
3	4	0.06701	0.17103	0.0064	1
4	5	0.01335	0.04211	0	1
4	7	0.0	0.20912	0	0.978
4	9	0	0.55618	0	0.969
5	6	0	0.25202	0	0.932
6	11	0.09498	0.19890	0	1

6	12	0.12291	0.25581	0	1
6	13	0.06615	0.13027	0	1
7	8	0.0	0.17615	0	1
7	9	0	0.11001	0	1
9	10	0.03181	0.08450	0	1
9	14	0.12711	0.27038	0	1
10	11	0.08205	0.19207	0	1
12	13	0.22092	0.19988	0	1
13	14	0.17093	0.34802	0	1

B) Programs

B.1. Greedy Algorithm

```
%optimal PMU placement function pmu=pmu_greedy5(num) clear all;
num=input('Enter The IEEE Standard Bus System Number:-');
linedata = linedatas(num);
fb=linedata(:,1);
tb=linedata(:,2);
fprintf('\n');
fprintf('\n');
fprintf('\n');
%to calculate connectivity matrix
or=zeros(num,num);
s=length(fb);
for i=1:s
or(fb(i),tb(i))=1;
or(tb(i),fb(i))=1;
end
[m,n]=size(or);
vis=zeros(m,n);
k=1;
w=0;
t=1;
adj=or;
vissum_prev=zeros(1,n);
while(k==1)
summ=sum(adj);     %row indicated summation of columns
X=max(summ);
r=0;
for i= 1:n
if(summ(i)==X)%check to see if max values occur more than once

r=r+1;
[row, col]=max(summ);%finds the column no. of bus with max connectivity
a(r)=col;
```

```
end
end

z=randperm(r);%creates a random matrix of integers with max value = r
col=a(z(1:1));%selects the 1st element if randomized z array   and assigns column value from c
matrix
adj(:,col)=0 ;
adj(col,:)=0;
vis(:,col)=or(:,col);
vis(col,:)=or(col,:);
vissum=sum(vis);
if min(vissum)==0
k=1;
else
k=0;
end
X=length(find(vissum));
y=length(find(vissum_prev));
if X==y
w=w;        %if visibilty remains the same dont place a pmu
else
w=w+1;
pmu_at(t)=col;
t=t+1;
end
col=0;
vissum_prev=vissum;
end
disp('total PMU used:')
fprintf(' %g', t-1);
fprintf('\n')
disp('PMU placed at buses:')
fprintf(' %g',pmu_at');
pmu_at=  sort(pmu_at)
```

B.2. Linearizing matrix using PMU

```
%construction of linearlized matrix
pmunew;
%newton;
fwls;
V;
%calculating the unit matrix whose missing voltages are removed.
e=zeros(14,14);
kk=length(pmu_at);
    for i=1:kk
    vv(i)=V(pmu_at(i));
    end
    vv  ;
u=length(vv);
for i=1:u
```

```
    e(pmu_at(i),pmu_at(i))=e(pmu_at(i),pmu_at(i))+1;
end
gg=e(pmu_at,:);
% Get YBus..
ybus = ybusppg(num)  ;
linedata = linedatas(num);      % Calling Linedatas...
fb = linedata(:,1);             % From bus number...
tb = linedata(:,2);             % To bus number...
r = linedata(:,3);              % Resistance, R...
x = linedata(:,4);              % Reactance, X...
b = linedata(:,5);              % Ground Admittance, B/2...
a = linedata(:,6);              % Tap setting value..
z = r + i*x     ;               % z matrix...
y = 1./z       ;                % inverse of each element...
% Calculating the diagonal element of admittances
yybus= diag(y) ;
%To calculate connectivity matrix of current incidence matrix
or=zeros(20,14);
 s=length(fb);
for i=1:s
    or(fb(i),tb(i))=1;
    or(tb(i),fb(i))=-1;
end
y_or=yybus * or;
%Calculate shunt admittance element....
nb = max(max(fb),max(tb)) ;    % No. of buses...
nl = length(fb)            ;   % No. of branches...
%Y = zeros(nb,nb);              % Initialise YBus...
aa=zeros(20,14);
 for m = 1:nb
     for n = 1:nl
           if fb(n) == m
             aa(m,m) = aa(m,m) + y(n)/(a(n)^2) + b(n);
           elseif tb(n) == m
              aa(m,m) = aa(m,m) + y(n) + b(n);
          end
      end
 end
 aa;
 %Combine the admittances
 y_comp=y_or+ aa;
 % generate measurement vector
 B=[gg;y_comp];
 %Deducing current
 I_comp= y_comp* V;
 %estimating result
 B_v=B*V;
 ww=length(B);
 W=.00004*eye(ww,ww);
 M= inv(B'* inv(W) *B)*B'*inv (W);      % conversion matrix
 x= inv(B'* inv(W) *B)*B'*inv (W)* B_v
```

B.3. VSI calculation

```
%For normal operating conditions(no load variation)
newton;
num=14;
linedata = linedatas(num);      % Calling Linedatas...
fb = linedata(:,1);             % From bus number...
tb = linedata(:,2);             % To bus number...
Y = ybusppg(nbus);              % Calling ybusppg.m to get Y-Bus Matrix..
r = linedata(:,3);              % Resistance, R...
x = linedata(:,4);              % Reactance, X...
z = r + i*x ;                   % z matrix...
Z = inv(Y);
X=imag(Z);
R=real(Z);
theta=angle(Z);
%calling variables from newton
V;
Ql;
del;
Pl;
for i=1:14
fvsi= (4*abs(Z(i))^2*Ql(i))/(V(i)^2*(X(i)));
Lmn = (4*(X(i))*Ql(i))/(V(i)*sin(theta(i)-(del(i)-del(i))))^2;
Lqp =  4*((X(i))/V(i)^2)*((Pl(i)^2 * (X(i))/V(i)^2)+Ql(i));
Pmax = (Ql(i)*R(i)/X(i))-((V(i)^2)*R(i))/(2*X(i)^2)+abs(Z(i))*V(i)*sqrt((V(i)^2)-
4*Ql(i)*X(i))/(2*X(i)^2);
Qmax = ((V(i)^2)/(4*X(i))-(Pl(i)^2)*X(i)/(V(i)^2));
vcpi1= abs(Pl(i)/Pmax);
vcpi2= abs(Ql(i)/Qmax);
end
V0;
bv=length(V);
for i=1:bv
   index(i)=V(i)/v0(i);
   i=i+1;
end
index;
```

B.4 Variable loading

```
nbus = 14;                  % IEEE-14, IEEE-30, IEEE-57..
T=zeros(20,1);
totaliter=zeros(20,1);
pmf=0.05;
num=14;
Pg_vr=zeros(num,1);
Qg_vr=zeros(num,1);
Pl_vr=zeros(num,1);
Ql_vr=zeros(num,1);
pf1=0.70;
tt=0;
```

```
busd = busdatas(nbus);         % Calling busdatas..
BMva = 100;                    % Base MVA..
bus = busd(:,1);               % Bus Number..
type = busd(:,2);              % Type of Bus 1-Slack, 2-PV, 3-PQ..
if num==14
Qmin = busd(:,9)/BMva;         % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva;        % Maximum Reactive Power Limit..
end
linedata = linedatas(num);     % Calling Linedatas...
fb = linedata(:,1);            % From bus number...
tb = linedata(:,2);            % To bus number...
r = linedata(:,3);             % Resistance, R...
x = linedata(:,4);             % Reactance, X...
b = linedata(:,5);             % Ground Admittance, B/2...
a = linedata(:,6);             % Tap setting value..
z = r + i*x;                   % z matrix...
y = 1./z;                      % To get inverse of each element...
b = i*b;                       % Make B imaginary...
nb = max(max(fb),max(tb));     % No. of buses...
nl = length(fb);               % No. of branches...
Y = zeros(nb,nb);              % Initialise YBus...
% Formation of the Off Diagonal Elements...
 for k = 1:nl
     Y(fb(k),tb(k)) = Y(fb(k),tb(k)) - y(k)/a(k);
     Y(tb(k),fb(k)) = Y(fb(k),tb(k));
 end
% Formation of Diagonal Elements....
 for m = 1:nb
     for n = 1:nl
         if fb(n) == m
             Y(m,m) = Y(m,m) + y(n)/(a(n)^2) + b(n);
         elseif tb(n) == m
             Y(m,m) = Y(m,m) + y(n) + b(n);
         end
     end
 end
G = real(Y);                   % Conductance matrix..
B = imag(Y);                   % Susceptance matrix..
upi;
 for ii=1:NS
         V_vr = busd(:,3);      % Specified Voltage..
         del_vr = busd(:,4);    % Voltage Angle..
         SPL=0.0;
         SQL=0.0;
         pf1=pf1+pmf;
         for k=1:num
             PL(k)=PLO(k,1)*pf1;
            QL(k)=QLO(k,1)*pf1;
            SPL=SPL+PL(k);
            SQL=SQL+QL(k);
         end
         for k=1:num
            PG(k)=SPL*UCP(k);
            QG(k)=SQL*UCQ(k);
         end
for s=2:num
    Pg_vr(s) = PG(s);           % PGi..
    Qg_vr(s) = QG(s);           % QGi.
    Pl_vr(s) = PLO(s)*pf1;      % PLi..
    Ql_vr(s) = QLO(s)*pf1;      % QLi..
end
```

```
Psp = Pg_vr - Pl_vr;                % Pi = PGi - PLi..
Qsp = Qg_vr - Ql_vr;                % Qi = QGi - QLi..
pv = find(type == 2 | type == 1);   % PV Buses..
pq = find(type == 3);               % PQ Buses..
npv = length(pv);                   % No. of PV buses..
npq = length(pq);                   % No. of PQ buses.
epsn = 1;                           %tolerance
itr = 1;
tstart=(tic);
while ( epsn>.00001 && itr<15  )    % Iteration starting..

% Calculate P and Q
 P = zeros(num,1);
 Q = zeros(num,1);
 for i = 1:num
    for k = 1:num
     P(i) = P(i) + V_vr(i)* V_vr(k)*(G(i,k)*cos(del_vr(i)-del_vr(k)) + B(i,k)*sin(del_vr(i)-del_vr(k)));
     Q(i) = Q(i) + V_vr(i)* V_vr(k)*(G(i,k)*sin(del_vr(i)-del_vr(k)) - B(i,k)*cos(del_vr(i)-del_vr(k)));
    end
 end
%%    Checking for Q-limit violations..
    if itr <= 7 && itr > 2      % Only checked up to 7th iterations..
        for n = 2:num
            if type(n) == 2
                QG = Q(n)+Ql_vr(n);
                if QG < Qmin(n)
%                       disp('lower limit is violated');
                    V_vr(n) = V_vr(n) + 0.01;
                elseif QG > Qmax(n)
                    V_vr(n) = V_vr(n) - 0.01;
%                       disp('upper limit is violated');
                end
            end
         end
    end
    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:num
        if type(i) == 3
            dQ(k,1) = dQa(i);
            k = k+1;
        end
    end
    dP = dPa(2:num);
    M = [dP; dQ];               % Mismatch Vector
    %% Formation of Jacobian Matrix
    %% J1 - Derivative of Real Power Injections with Angles..
    J1 = zeros(num-1,num-1);
    for i = 1:(num-1)
        m = i+1;
        for k = 1:(num-1)
            n = k+1;
            if n == m
                for n = 1:num
                    J1(i,k) = J1(i,k) + V_vr(m)* V_vr(n)*(-G(m,n)*sin(del_vr(m)-del_vr(n)) + B(m,n)*cos(del_vr(m)-
del_vr(n)));
                end
                J1(i,k) = J1(i,k) - V_vr(m)^2*B(m,m);
```

```
        else
            J1(i,k) = V_vr(m)* V_vr(n)*(G(m,n)*sin(del_vr(m)-del_vr(n)) - B(m,n)*cos(del_vr(m)-del_vr(n)));
        end
    end
end

% J2 - Derivative of Real Power Injections with V_vr..
J2 = zeros(num-1,npq);
for i = 1:(num-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:num
                J2(i,k) = J2(i,k) + V_vr(n)*(G(m,n)*cos(del_vr(m)-del_vr(n)) + B(m,n)*sin(del_vr(m)-del_vr(n)));
            end
            J2(i,k) = J2(i,k) + V_vr(m)*G(m,m);
        else
            J2(i,k) = V_vr(m)*(G(m,n)*cos(del_vr(m)-del_vr(n)) + B(m,n)*sin(del_vr(m)-del_vr(n)));
        end
    end
end
%% J3 - Derivative of Reactive Power Injections with Angles..
J3 = zeros(npq,num-1);
for i = 1:npq
    m = pq(i);
    for k = 1:(num-1)
        n = k+1;
        if n == m
            for n = 1:num
                J3(i,k) = J3(i,k) + V_vr(m)* V_vr(n)*(G(m,n)*cos(del_vr(m)-del_vr(n)) + B(m,n)*sin(del_vr(m)-
del_vr(n)));
            end
            J3(i,k) = J3(i,k) - V_vr(m)^2*G(m,m);
        else
            J3(i,k) = V_vr(m)* V_vr(n)*(-G(m,n)*cos(del_vr(m)-del_vr(n)) - B(m,n)*sin(del_vr(m)-del_vr(n)));
        end
    end
end

%% J4 - Derivative of Reactive Power Injections with V_vr..
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:num
                J4(i,k) = J4(i,k) + V_vr(n)*(G(m,n)*sin(del_vr(m)-del_vr(n)) - B(m,n)*cos(del_vr(m)-del_vr(n)));
            end
            J4(i,k) = J4(i,k) - V_vr(m)*B(m,m);
        else
            J4(i,k) = V_vr(m)*(G(m,n)*sin(del_vr(m)-del_vr(n)) - B(m,n)*cos(del_vr(m)-del_vr(n)));
        end
    end
end
J = [J1 J2; J3 J4];             % Jacobian Matrix..
tstart=(tic);
 X =inv(J)*M;                   % Correction Vector
Tnr=toc(tstart);
dTh = X(1:num-1);                % Change in Voltage Angle..
```

```
    dV = X(num:end);                  % Change in Voltage Magnitude..
    %% Updatation of  State Vectors..
del_vr(2:num) = dTh + del_vr(2:num);    % Voltage Angle..
k = 1;
for i = 2:num
   if type(i) == 3
   V_vr(i) = dV(k) + V_vr(i);           % Voltage Magnitude..
   k = k+1;
   end
end
    itr = itr + 1;
    epsn =max(abs(M));                 % Tolerance..
end
T=toc(tstart);
Totalitr=itr;
    disp('For load-')
     disp(pf1);
P_nr = zeros(num,1);
Q_nr = zeros(num,1);
for i = 1:num
    for k = 1:num
        P_nr(i) = P_nr(i) + V_vr(i)* V_vr(k)*(G(i,k)*cos(del_vr(i)-del_vr(k)) + B(i,k)*sin(del_vr(i)-del_vr(k)));
        Q_nr(i) = Q_nr(i) + V_vr(i)* V_vr(k)*(G(i,k)*sin(del_vr(i)-del_vr(k)) - B(i,k)*cos(del_vr(i)-del_vr(k)));
    end
end
 all_data(((tt*num)+1):((tt*num)+num),1:2)=[P_nr Q_nr];
  all_vdata(((tt*num)+1):((tt*num)+num),1:2)=[V_vr del_vr];
  tt=tt+1;
disp('#########################################################################################
############################################');
disp('-------------------------------------------------------------------------------------------------------------------------
--');
disp(' |  P_nr      |   Q_nr     |        V_vr       | del_vr  ');
for a=1:num
disp('-------------------------------------------------------------------------------------------------------------------------
--');
 fprintf('  %9.4f',P_nr(a)*100);  fprintf('      %9.4f',Q_nr(a)*100);  fprintf('      %9.4f',V_vr(a)); fprintf('
%9.4f',del_vr(a));
fprintf('\n');
end
disp('-------------------------------------------------------------------------------------------------------------------------
--');
disp('#########################################################################################
#####################################################');
 end
```

B.5 Eigen value calculation

```
%calculation of reduced jacobian matrix
newton;  % calling NR program
J;      % calling jacobian matrix
dPa = 0;
for nn=1:num
     Pl(nn)=Pl(nn)+50;
     nn=nn+1;
 end
 Pl
dQa = Qsp-Q
J5=inv(J1);
JR = [ J4-J3*J5*J2] %reduced jacobian matrix
dQa= JR *dV;
```

```
e=length(JR);
[B,D,W]=eig(JR)     % left,diagonal,right matrix of eigen value
JR=B*D*W;
JJR=B*inv(D)*W;
dV=JJR*dQa;
lambda=inv(D);
dV= ((B*W)/lambda)* dQa
for k=1:e
  for i=1:e
  particip(k,i)=B(k,i)* W(i,k);
  end
end
```

B.6 State estimation using WLS

```
% Power System State Estimation using Weighted Least Square Method..
num= 14;                       % IEEE - 14 or IEEE - 30 bus system
Y = ybusppg(num);
zdata = zdatas(num);          % Get Measurement data..
bpq = bbusppg(num);            % Get B data..
nbus = max(max(zdata(:,4)),max(zdata(:,5))); % Get number of buses..
type = zdata(:,2); % Type of measurement, Vi - 1, Pi - 2, Qi - 3, Pij - 4, Qij - 5, Iij - 6..
z = zdata(:,3);               % Measuement values..
fbus = zdata(:,4);              % From bus..
tbus = zdata(:,5);              % To bus..
Ri = diag(zdata(:,6));          % Measurement Error..
V = ones(nbus,1);               % Initialize the bus voltages..
del = zeros(nbus,1);            % Initialize the bus angles..
E = [del(2:end); V];            % State Vector..
G = real(Y);
B = imag(Y);
vi = find(type == 1);           % Index of V measurements..
ppi = find(type == 2);           % Index of P injection measurements..
qi = find(type == 3);           % Index of Q injection measurements..
pf = find(type == 4);           % Index of P powerflow measurements..
qf = find(type == 5);           % Index of Q powerflow measurements..
nvi = length(vi);              % Number of V measurements..
npi = length(ppi);              % Number of P Injection measurements..
nqi = length(qi);              % Number of Q Injection measurements..
npf = length(pf);              % Number of P Flow measurements..
nqf = length(qf);              % Number of Q Flow measurements..
iter = 1;
tol = 5;
while(tol>1e-4)
   %Measurement Function, h
   h1 = V(fbus(vi),1);
   h2 = zeros(npi,1);
   h3 = zeros(nqi,1);
   h4 = zeros(npf,1);
   h5 = zeros(nqf,1);
   for i = 1:npi
      m = fbus(ppi(i));
      for k = 1:nbus
         h2(i) = h2(i) + V(m)*V(k)*(G(m,k)*cos(del(m)-del(k)) + B(m,k)*sin(del(m)-del(k)));
      end
   end
   for i = 1:nqi
      m = fbus(qi(i));
      for k = 1:nbus
         h3(i) = h3(i) + V(m)*V(k)*(G(m,k)*sin(del(m)-del(k)) - B(m,k)*cos(del(m)-del(k)));
      end
```

```
    end
    for i = 1:npf
        m = fbus(pf(i));
        n = tbus(pf(i));
        h4(i) = -V(m)^2*G(m,n) - V(m)*V(n)*(-G(m,n)*cos(del(m)-del(n)) - B(m,n)*sin(del(m)-del(n)));
    end
    for i = 1:nqf
        m = fbus(qf(i));
        n = tbus(qf(i));
        h5(i) = -V(m)^2*(-B(m,n)+bpq(m,n)) - V(m)*V(n)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-
del(n)));
    end
    h = [h1; h2; h3; h4; h5];
    % Residue..
    r = z - h;
    % Jacobian..
    % H11 - Derivative of V with respect to angles.. All Zeros
    H11 = zeros(nvi,nbus-1);
    % H12 - Derivative of V with respect to V..
    H12 = zeros(nvi,nbus);
    for k = 1:nvi
        for n = 1:nbus
            if n == k
                H12(k,n) = 1;
            end
        end
    end
    % H21 - Derivative of Real Power Injections with Angles..
    H21 = zeros(npi,nbus-1);
    for i = 1:npi
        m = fbus(ppi(i));
        for k = 1:(nbus-1)
            if k+1 == m
                for n = 1:nbus
                    H21(i,k) = H21(i,k) + V(m)* V(n)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
                end
                H21(i,k) = H21(i,k) - V(m)^2*B(m,m);
            else
                H21(i,k) = V(m)* V(k+1)*(G(m,k+1)*sin(del(m)-del(k+1)) - B(m,k+1)*cos(del(m)-del(k+1)));
            end
        end
    end
    % H22 - Derivative of Real Power Injections with V..
    H22 = zeros(npi,nbus);
    for i = 1:npi
        m = fbus(ppi(i));
        for k = 1:(nbus)
            if k == m
                for n = 1:nbus
                    H22(i,k) = H22(i,k) + V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
                end
                H22(i,k) = H22(i,k) + V(m)*G(m,m);
            else
                H22(i,k) = V(m)*(G(m,k)*cos(del(m)-del(k)) + B(m,k)*sin(del(m)-del(k)));
            end
        end

    end
    % H31 - Derivative of Reactive Power Injections with Angles..
    H31 = zeros(nqi,nbus-1);
    for i = 1:nqi
```

```
    m = fbus(qi(i));
    for k = 1:(nbus-1)
        if k+1 == m
            for n = 1:nbus
                H31(i,k) = H31(i,k) + V(m)* V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            H31(i,k) = H31(i,k) - V(m)^2*G(m,m);
        else
            H31(i,k) = V(m)* V(k+1)*(-G(m,k+1)*cos(del(m)-del(k+1)) - B(m,k+1)*sin(del(m)-del(k+1)));
        end
    end

end
% H32 - Derivative of Reactive Power Injections with V..
H32 = zeros(nqi,nbus);
for i = 1:nqi
    m = fbus(qi(i));
    for k = 1:(nbus)
        if k == m
            for n = 1:nbus
                H32(i,k) = H32(i,k) + V(n)*(G(m,n)*sin(del(m)-del(n)) - B(m,n)*cos(del(m)-del(n)));
            end
            H32(i,k) = H32(i,k) - V(m)*B(m,m);
        else
            H32(i,k) = V(m)*(G(m,k)*sin(del(m)-del(k)) - B(m,k)*cos(del(m)-del(k)));
        end
    end

end
% H41 - Derivative of Real Power Flows with Angles..
H41 = zeros(npf,nbus-1);
for i = 1:npf
    m = fbus(pf(i));
    n = tbus(pf(i));
    for k = 1:(nbus-1)
        if k+1 == m
            H41(i,k) = V(m)* V(n)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
        else if k+1 == n
            H41(i,k) = -V(m)* V(n)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
            else
                H41(i,k) = 0;
            end
        end
    end
end
% H42 - Derivative of Real Power Flows with V..
H42 = zeros(npf,nbus);
for i = 1:npf
    m = fbus(pf(i));
    n = tbus(pf(i));
    for k = 1:nbus
        if k == m
            H42(i,k) = -V(n)*(-G(m,n)*cos(del(m)-del(n)) - B(m,n)*sin(del(m)-del(n))) - 2*G(m,n)*V(m);
        else if k == n
            H42(i,k) = -V(m)*(-G(m,n)*cos(del(m)-del(n)) - B(m,n)*sin(del(m)-del(n)));
            else
                H42(i,k) = 0;
            end
        end
    end
end
```

```
    % H51 - Derivative of Reactive Power Flows with Angles..
    H51 = zeros(nqf,nbus-1);
    for i = 1:nqf
        m = fbus(qf(i));
        n = tbus(qf(i));
        for k = 1:(nbus-1)
            if k+1 == m
                H51(i,k) = -V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) - B(m,n)*sin(del(m)-del(n)));
            else if k+1 == n
                H51(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) - B(m,n)*sin(del(m)-del(n)));
                else
                    H51(i,k) = 0;
                end
            end
        end
    end
    % H52 - Derivative of Reactive Power Flows with V..
    H52 = zeros(nqf,nbus);
    for i = 1:nqf
        m = fbus(qf(i));
        n = tbus(qf(i));
        for k = 1:nbus
            if k == m
                H52(i,k) = -V(n)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n))) - 2*V(m)*(-B(m,n)+
bpq(m,n));
            else if k == n
                H52(i,k) = -V(m)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
                else
                    H52(i,k) = 0;
                end
            end
        end
    end
    % Measurement Jacobian, H..
    H = [H11 H12; H21 H22; H31 H32; H41 H42; H51 H52];
    % Gain Matrix, Gm..
    Gm = H'*inv(Ri)*H;
    %Objective Function..
    J = sum(inv(Ri)*r.^2);
    % State Vector..
    dE = inv(Gm)*(H'*inv(Ri)*r);
    E = E + dE;
    del(2:end) = E(1:nbus-1);
    V = E(nbus:end);
    iter = iter + 1;
    tol = max(abs(dE));
end
CvE = diag(inv(H'*inv(Ri)*H)); % Covariance matrix..
Del = 180/pi*del;
% Bus Voltages and angles..
E2 = [V Del];
disp('--State Estimation--------');
disp('--------------------------');
disp('| Bus |    V   |  Angle  | ');
disp('| No  |   pu   |  Degree | ');
disp('--------------------------');
for m = 1:num
fprintf('%4g', m); fprintf('  %8.4f', V(m)); fprintf('   %8.4f', Del(m)); fprintf('\n');
end
disp('----------------------------');
```

thesis

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